



THE OPTIMIZATION OF TRAFFIC SIGNAL TIMING FOR EMERGENCY EVACUATION USING THE SIMULATED ANNEALING ALGORITHM

Arash Jahangiri¹, Shahriar Afandizadeh², Navid Kalantari³

Dept of Civil Engineering, Iran University of Science and Technology, Narmak, Tehran, Iran
E-mails: ¹jahangiri.ar@gmail.com; ²zargari@iust.ac.ir (corresponding author); ³kalantari@iust.ac.ir

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Abstract. In recent years, natural and man-made disasters have increased and consequently put people's lives in danger more than before. Some of the crises are predictable. In these cases, there is a limited time for effective respond minimizing fatalities when people should be evacuated in a short time. Therefore, a transportation network plays a key role in evacuation. Hence, the outbound paths of urban networks are not sufficient from the viewpoint of number and capacity to encounter a huge amount of people; furthermore, it is costly to construct new routes or increase the capacity of the existing ones. Thus, a better utilization of the existing infrastructure should be considered. The article presents a model that determines optimum signal timing and increases the outbound capacity of the network. Moreover, in regard for the magnitude of the problem, an optimal solution could not be reached employing ordinary methods; therefore, the simulated annealing algorithm which is a meta-heuristic technique is used. The results of this study demonstrated that the objective function of the problem was greatly improved.

Keywords: crisis, emergency evacuation, signal timing, simulated annealing algorithm.

1. Introduction

For the last 30 years, natural and man-made disasters have been increased. Urban areas are threatened with hurricanes, tornados, floods, earthquakes, tsunamis, volcanic eruptions, incidents in power plants and chemical industry or using general dangerous materials, fires, etc.

Among these, some incidents like hurricanes are predictable while for some others like earthquakes there isn't any reliable method for prediction. In the cases that could be predicted, minutes and even seconds are distances between death and life (Pielke 1998). Therefore, in these situations, there is a limited time for effective respond minimizing fatalities, and thus advanced planning is an effective solution to respond with flexibility, coordination and speed. People should be evacuated in a short time. Evacuation may include hundreds or even thousands of people. Therefore, a transportation network plays a key role.

Previous experiences have indicated that the main issue in emergency evacuation is that the outbound paths of urban networks are not sufficient from the viewpoint of number and capacity to encounter a large amount of people; furthermore, it is costly to construct new routes or increase the capacity of the existing ones. Thus, a better utilization of the existing infrastructure should be considered (Yuan 2005). The latter issue along with signal timing is optimized in the paper.

The main purpose of emergency evacuation planning is to transport people from a dangerous area to a safe region. A lot of strategies were proposed to help people with moving faster. One of the strategies is planning signal timing. It is possible to increase the outbound capacity of a network by resetting signal timing via giving the majority of green time to the main evacuation routes.

Several factors are effective in the determination and implementation of signal timing in critical situations; high demand for travelling occurs in a short period of time (Wolshon, Meehan 2003). Inbound traffic may cause severe congestions, for example household members first find each other and then start evacuation. Another problem is that people's behavior is frequently unpredictable due to crisis situations and this may cause more traffic incidents than under normal situations. Also, roadside parking affects network capacity during evacuation. Moreover, those having no personal vehicles, require public transportation.

First, the article reviews the previous studies on signal timing in urban evacuation. Then, the simulated annealing algorithm as a meta-heuristic method used to solve the problem is presented. In the next section, model formulation is introduced. Finally, the model is applied for Hashtgerd city as a case study and the results are illustrated in the last part.

2. Literature Review

Some investigations into signal timing in urban evacuation were conducted in the past. Those included the simulation of emergency evacuation by CORSIM, the optimization of signal timing plans by SYNCHRO and TRANSYT-7F, the evaluation of EVP (Emergency vehicle preemption) via TSIS, CORSIM and an empirical evaluation of EVP. Some interviews have been conducted involving experts so that to understand the present approaches to signal timing and the evaluation of these approaches. This section of the paper reviews the above mentioned studies.

Franzese and Han (2001) proposed a computer-based model to simulate traffic flow in emergency evacuation and to evaluate the impacts of several traffic management strategies. They illustrated that traffic management had a great impact on the effectiveness of evacuation plans. They focused on several traffic management strategies such as contra flow plans.

Sisiopiku *et al.* (2004) used CORSIM to test the proposed evacuation plans and response actions. In their work, the effect of signal timing optimization as a traffic management strategy in a small region in Birmingham, Alabama was evaluated. They used SYNCHRO to optimize signal timing plans. They suggested that the optimization of signal timing considerably reduced delays.

Emergency vehicle preemption (EVP) could have improved response time of emergency vehicles in intersections and facilitated the movement of these vehicles, however, this facilitation may influence other road users. Therefore, it is required to evaluate the implementation benefits and costs of EVP as a part of an evacuation plan.

Bullock *et al.* (1999) used TSIS to evaluate the impacts of EVP systems on traffic flows in 3 coordinated intersections in Loudon County, Virginia. In the simulated model, emergency vehicles were modeled as a regular car with a very aggressive driver.

McHale and Collura (2003) modeled emergency vehicles with CORSIM and used optimum signal timing plans that were concluded from TRANSYT-7F to evaluate the impacts of EVP on all passengers.

Louisell (2005) mentioned that limitations on simulation-based approaches made them insufficient to evaluate the impacts of EVP on network performance. Therefore, they empirically evaluated the benefits of EVP on intersection performance based on extensive observations in the Northern Virginia region. They considered the interactions between emergency vehicles, other driver's behavior and signal timing plans.

Louisell *et al.* (2003) proposed a conflict analysis method to evaluate the potential of EVP safe conflicts. Empirical analysis indicated that conflict points between the paths of emergency vehicles and traffic flow paths were greatly reduced by EVP. Louisell *et al.* (2004) in another study developed a worksheet method to evaluate the safety benefits of EVP; this method estimated accident reduction at an intersection or within a corridor. By using this method, the intersections and corridors further improved via EVP are recognized.

Widespread interviews with experts and agents in federal, state and local agencies were carried out by

Miller-Hooks and Tarnoff (2005) in the United States between September 2004 and February 2005. These interviews illustrated that there were 4 approaches to setting signal timing:

- 1) set signals on flash;
- 2) control signals by police at critical intersections;
- 3) set signals on PM-peak setting;
- 4) set signal timing plans on maximum cycle length on evacuation routes, giving the majority of green time to the major directions.

Chen (2005) used CORSIM and developed a simulation model for recognizing the performance of signal timing plans in Washington D.C. Among the approaches mentioned before, approaches 1, 3 and 4 were tested under different scenarios. There are two general approaches for setting signals on flash:

- 1) Yellow flash on the main direction, red flash on the minor direction (YR). In this state, priority is given to traffic on the main directions. A drawback of this approach is that extremely long delays may occur for vehicles on the minor directions and so drivers may not be willing to obey traffic rules.
- 2) Red flash in all directions (4R). In this state, vehicles at each intersection are served on a first-come first-serve basis. In approaches 3 and 4, cycle lengths are 100 and 240 seconds respectively. In each scenario, two states with different travel demand were considered and six signal timing plans were tested.

The obtained results have shown that when travel demand is heavy, higher cycle length is better and vice versa. Hence, we can say that the intensity of travel demand determines cycle length.

3. Simulated Annealing Algorithm

We frequently encounter combinatorial optimization problems in many contexts such as management science, computer science, industrial and electrical engineering etc. When dealing with such problems, we are given a finite or countably infinite set of solutions from which we have to find the one that minimizes or maximizes the given function (Michiels *et al.* 2007). This function is usually called a cost function or an objective function and demonstrates the goodness of a complex system. The cost function depends on minute configuration of every part of that system (Kirkpatrick *et al.* 1983). The major achievement of combinatorial optimization is the development of the computational complexity theory that formalizes the difference between easy and hard problems. A problem is called easy in case it can be solved applying a polynomial-time algorithm, i.e. an algorithm solves a problem supposing that it always returns to an optimal solution. A problem is called hard, formally referred to as NP-hard in case it is commonly believed that the polynomial-time algorithm that solves it does not exist. Many combinatorial optimization problems have this property. We can use heuristic algorithms to solve these problems. However, solutions found employing these methods are not certainly global optimums. Nevertheless, they can be reached in a reasonable time.

Hence, heuristic algorithms contain trade-off between optimization and runtime.

The heuristic methods that are generally called iterative improvement algorithms only permit downhill moves and are trapped in local optimums.

To solve this difficulty, meta-heuristic algorithms are used, which in contrary to iterative improvement methods, are not stopped in first local optimum. The simulated annealing algorithm used in this article is applied for some methods to perform non-improving moves so that it is not trapped in local optimums.

Simulated annealing (SA) algorithm steps (Glover, Kochenberger 2003) are as follows:

- Step 1.** Choose the initial solution, s .
- Step 2.** Choose a counter for changing temperature, $k = 0$.
- Step 3.** Choose a cooling schedule. (t_k : temperature in iteration k)
- Step 4.** Choose the initial temperature, T .
- Step 5.** Choose the number of iterations at any temperature (M_k).
- Step 6.** Repeat until stop criteria:
 - Set $m = 0$.
 - Repeat:
 - Generate a new solution
 - Calculate the difference between the current cost function and new cost function values. (Δ)
 - If $\Delta \leq 0$, then, a new solution is replaced with the current solution; if $\Delta > 0$, then, a new solution is replaced with the current solution to the probability of $\exp(-\Delta/t_k)$.
 - $m = m + 1$.
 - Until $m = M_k$.
 - $k = k + 1$.

Simulated annealing flowchart (Pham, Karaboga 2000) is illustrated in Fig. 1.

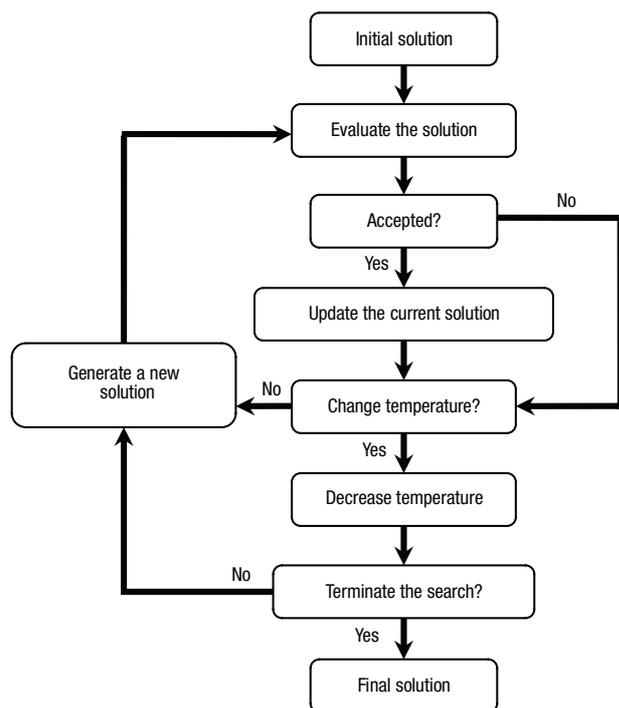


Fig. 1. Simulated annealing flowchart

4. Problem Formulation

Optimizing signal timing plans is a bi-level problem. The objective function of the main problem is to minimize the total travel time of network users; this problem itself requires a solution to a simultaneous distribution-assignment sub-problem. Distribution and assignment steps in the modeling process are simultaneously performed because origin-destination demands are not recognized in crisis situations on the one hand and there is no statistical data on the other. Moreover, in these situations, travel destinations (shelters) might be changed during evacuation, i.e. before starting evacuation, each person has an initial path in his/her mind to reach a specific shelter, but in regard with traffic situations, they might change their initial destinations.

To solve the main problem, the simulated annealing algorithm is applied. While accomplishing this procedure, to solve the sub-problem (distribution-assignment problem), a double-stage algorithm is used because the convergence of the double-stage algorithm is considerably faster than the convergence of the convex combination algorithm for solving logit based distribution-assignment problems (Sheffi 1985).

The formulation of the problem is as follows:

$$\min \sum_{a \in R} x_a(ST) t_a^{ST}(x_a(ST)); \tag{1}$$

$$s.t.: \{ST = ((g/C)_1, (g/C)_2, \dots, (g/C)_e); 0 < (g/C)_i < 1\}; \tag{2}$$

$$\min z(x, q) = \sum \int_0^{x_a} t_a(w) dw + \frac{1}{\gamma} \sum_{rs} (q_{rs} \ln q_{rs} - q_{rs}) - \sum_{rs} M_s q_{rs}; \tag{3}$$

$$s.t.: \sum_k f_k^{rs} = q_{rs} \quad \forall r, s; \tag{4}$$

$$\sum q_{rs} = O_r \quad \forall r; \tag{5}$$

$$f_k^{rs} \geq 0 \quad \forall k, r, s. \tag{6}$$

The definitional constraint:

$$x_a = \sum_r \sum_s \sum_k f_k^{rs} \delta_{a,k}^{rs} \quad \forall a \text{ is also a part of this program.}$$

The parameters of the model are defined below:

- r – a set of network links;
- e – the number of signalized intersections;
- g – green time;
- C – cycle length;
- $((g/C)_1, (g/C)_2, \dots, (g/C)_e) = ST$ – a chosen signal timing plan;
- a – represent a link;
- $x_a(ST)$ – equilibrium flow on link a when ST is chosen as a signal timing plan;
- t_a^{ST} – a performance function of link a when ST is chosen as a signal timing plan;
- M_s – attraction measure for destination s ; this measure can be a function of capacity (or the probability of the existing empty space) and the existing facilities of desti-

nation s . In reality, people try to accomplish two goals: to travel to the destination with the highest attraction measure while spending the least possible time in traveling (Sheffi 1985);

q_{rs} – ravel demand from origin r to destination s ;
 f_k^{rs} – traffic flow on path k from origin r to destination s ;
 O_r – trip generation from origin r ;

$$\delta_{a,k}^{rs} \text{ (indicator variable)} = \begin{cases} 1 & \text{if link } a \text{ is on path } k; \\ & \text{between O-D pair } r-s; \\ 0 & \text{otherwise.} \end{cases}$$

Steps of the Double stage algorithm (Sheffi 1985) are as follows:

Step 0. Initialization. Find a set of feasible flows

$$\{q_{rs}^n\}, \{x_a^n\}. \text{ Set } n = 1.$$

Step 1. Travel time update. Calculate $t_a^n = t_a(x_a^n), \forall a$.

Step 2. Direction finding:

- a) Calculate the shortest travel time path from each origin, r , to all destinations based on t_a^n . Let u_{rs}^n denote the shortest travel time from r to s .
- b) Determine auxiliary O-D flows by applying logit-distribution:
The model, that is,

$$v_{rs}^n = O_r \frac{\exp(-\gamma(u_{rs}^n - M_s))}{\sum_m \exp(-\gamma(u_{rm}^n - M_m))}. \quad (7)$$

- c) Assign v_{rs}^n to the minimum travel time path (identified above) between r and s .

Step 3. Move size determination. Find α_n that solves program:

$$\min z(\alpha) = \sum_a \int_0^{x_a^n + \alpha(y_a^n - x_a^n)} t_a(w) dw +$$

$$\frac{1}{\gamma} \sum_{rs} \left[q_{rs}^n + \alpha(v_{rs}^n - q_{rs}^n) \right] \left\{ \ln \left[q_{rs}^n + \alpha(v_{rs}^n - q_{rs}^n) \right] - 1 - \gamma M_s \right\},$$

$$0 \leq \alpha \leq 1. \quad (8)$$

Step 4. Flow update. Set:

$$x_a^{n+1} = x_a^n + \alpha_n (y_a^n - x_a^n); \quad (9)$$

$$q_{rs}^{n+1} = q_{rs}^n + \alpha_n (v_{rs}^n - q_{rs}^n). \quad (10)$$

Step 5. Convergence test. If convergence is not achieved, set $n=n+1$ and go to Step 1. Otherwise, terminate; the solution is $\{q_{rs}^{n+1}\}, \{x_a^{n+1}\}$.

The time of crisis occurrence is extremely important. For instance, in case it occurs at midday, people first try to find their household members and secure their possessions and then start evacuating, but at night, the stage of finding household members will be eliminated. However, the focus of this study is on time when household members are found, gathered together, their possessions are secured and evacuation has begun. For example, if the objective function of the main problem was total evacuation time, in regard to the time of the

event, reasonable time would be assumed until family members found each other and secured their possessions; this period of time must be added to the objective function of the main problem.

5. Computational Experience

In our case, Hashtgerd city is chosen as a case study. There are several industries in the northern parts of the city, and thus there is a probability that a crisis will occur in these parts of the city and dangerous materials will spread towards the urban areas. Therefore, an emergency evacuation plan should be considered for Hashtgerd city. An urban network is shown in Fig. 2. The network is made of 76 nodes and 115 links. It is assumed that there are 9 signalized intersections (nodes 28, 31, 46, 51, 52, 57, 60, 63, 65). As the link performance function, the well-known BPR function ($t_a(v_a) = t_{0a}[1 + 0.15(v_a/c_a)^4]$) is used. In this function, t_a is travel time of link a , v_a is traffic volume on link a per one meter width, t_{0a} is travel time with free flow speed and c_a is the capacity of link a per one meter width. For delays on intersections, the following functions are applied.

Signalized intersections (Report No 05: Delay... 1997):

$$D = \frac{(C-g)^2}{2C(1-v/s)} + 43 \left(\frac{v}{(g/C) \cdot s} \right)^4, \quad (11)$$

where: D – delay for passing an intersection on entering link; v – traffic volume on entering link per one meter width; s – the exiting rate of traffic volume per one meter width.

Unsignalized intersections (Report No 04: Delay... 1997):

$$t_a(v_a) = (t_{0a}[1 + 0.8(v_a/c_a)^2]) / 60. \quad (12)$$

Where all parameters are the same as the parameters of link performance functions

It is assumed that 100% of people in the zones closer to the danger area and 80% of those in other zones have been evacuated. When choosing a mode, it is assumed that 70% of households having personal vehicles travel with their own car while others use buses for evacuation.

As mentioned before, trip distribution and trip assignment steps are performed simultaneously. To implement these steps, a program is written in MATLAB workspace. Nodes 75 and 76 are considered as shelters and destinations of trips. Attraction measures for nodes 75 and 76 are assumed to be 3 and 6 respectively which means that the probability of the existing empty space or existing facilities at destination 76 is twice higher than those at destination 75.

The steps of the simulated annealing algorithm are also written in MATLAB workspace. Before running the program, some decisions must be made. These decisions are summarized in Table 1.

Every solution represents a signal timing plan; it is assumed that for the initial solution, cycle length equals 120 seconds and g/C value equals 0.5 for every phase in all signalized intersections. In every step of the algo-

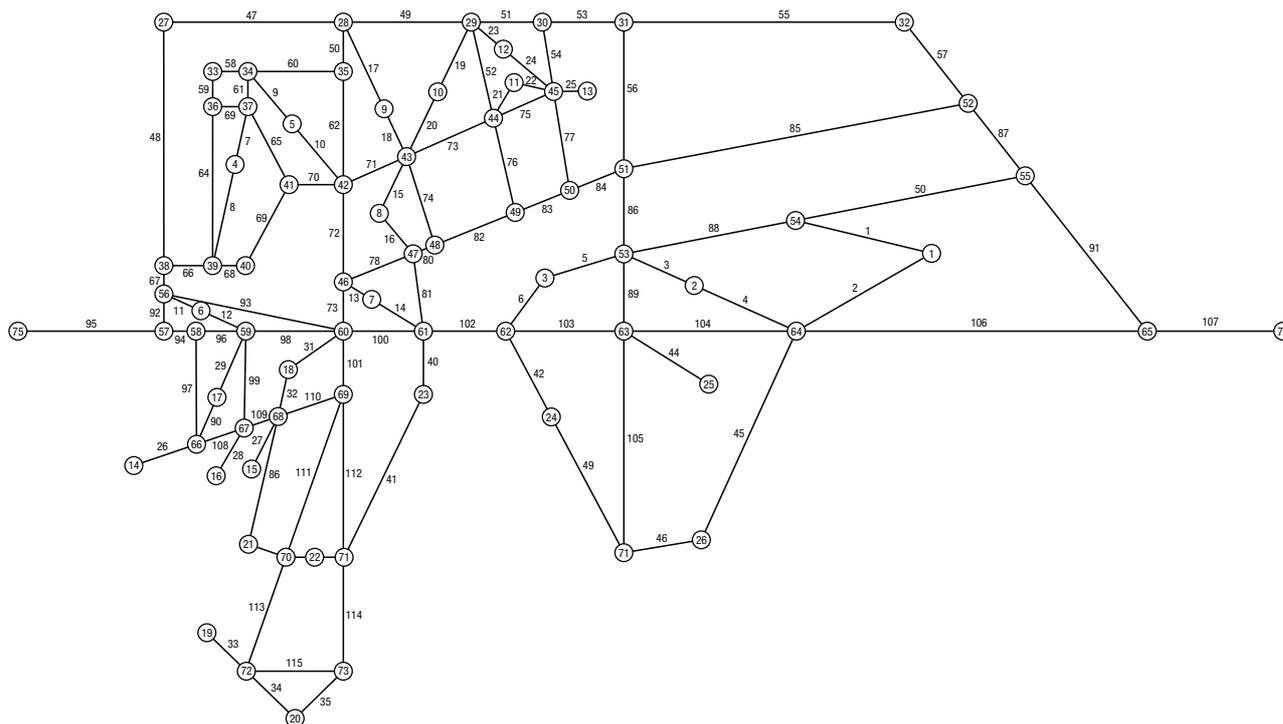


Fig. 2. The urban network of study area (9 unsignalized intersections are illustrated by squares)

Table 1. Decisions related to the SA algorithm

General decisions related to SA algorithm	Decisions on cooling schedules
Initial solution	Initial temperature
Generation of a new solution	The number of iterations at each temperature
Evaluation of a new solution	The temperature reduction method
	Final temperature

algorithm, one intersection is randomly selected and then a random number between 0 and 1 is generated and replaced with the current g/C value of an intersection phase to generate a new solution. After the generation of the new solution, this solution must be evaluated. For evaluation, comparative difference in objective function values is considered as follows.

$$\Delta C_{ij} = (C_j - C_i) / C_j, \tag{13}$$

where: ΔC_{ij} – comparative difference in objective function values; C_j – an objective function value of new solution j ; C_i – objective function values of current solution i .

Furthermore, the model is tested for five states with the cycle lengths of 120, 160, 200, 240 and 280 seconds.

To determine the aforementioned four parameters, try and error method is used. For temperature reduction, in every step of the algorithm, the current temperature is multiplied by a number less than 1 and close to it. First, the values of 0.4, 10, 0.85, and 0.005 are chosen as an initial guess for the parameters. This state is called the base situation. To determine the best values of these parameters, sensitivity analysis is carried out; for each parameter, four other values (shown in Table 2) are tested and the best value of each parameter is obtained; then, a new state considering these best values is tested. The obtained results are shown in Tables 3–6 and displayed in Figs 3–6. Finally, the best result occurred with the values of 0.4, 10, 0.85 and 0.003 for the initial temperature, the number of iterations at each temperature, temperature reduction coefficient and final temperature.

Table 2. Variations in each parameter of sensitivity analysis

Parameter	Variations				
Initial temperature	0.2	0.3	0.4	0.5	0.6
Number of iterations at each temperature	6	8	10	12	14
Temperature reduction coefficient	0.8	0.83	0.85	0.87	0.9
Final temperature	0.0003	0.0004	0.0005	0.0006	0.0007

Table 3. Sensitivity analysis (parameter under scrutiny: initial temperature)

Row	Initial temperature	Number of iterations at each temperature	Temperature reduction coefficient	Final temperature	Objective function
1	0.2	10	0.85	0.0005	40203
2	0.3	10	0.85	0.0005	39865
3 (base situation)	0.4	10	0.85	0.0005	39023
4	0.5	10	0.85	0.0005	40107
5	0.6	10	0.85	0.0005	41075

Table 4. Sensitivity analysis (parameter under scrutiny: the number of iterations at each temperature)

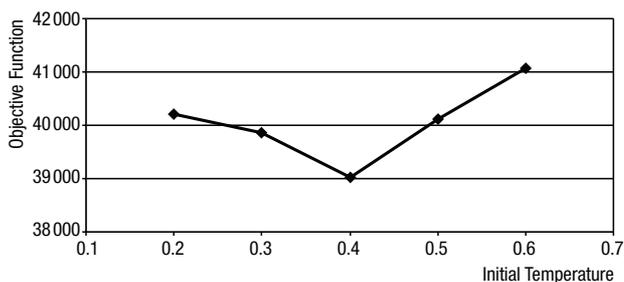
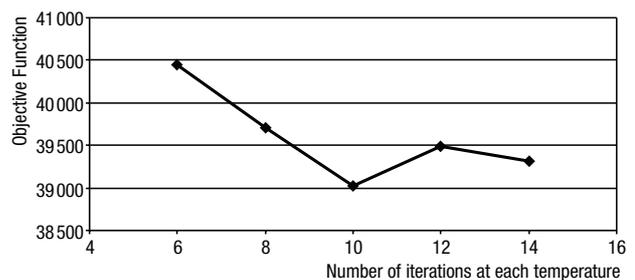
Row	Initial temperature	Number of iterations at each temperature	Temperature reduction coefficient	Final temperature	Objective function
1	0.4	6	0.85	0.0005	40454
2	0.4	8	0.85	0.0005	39713
3 (base situation)	0.4	10	0.85	0.0005	39023
4	0.4	12	0.85	0.0005	39485
5	0.4	14	0.85	0.0005	39309

Table 5. Sensitivity analysis (parameter under scrutiny: temperature reduction coefficient)

Row	Initial temperature	Number of iterations at each temperature	Temperature reduction coefficient	Final temperature	Objective function
1	0.4	10	0.8	0.0005	40111
2	0.4	10	0.83	0.0005	39602
3 (base situation)	0.4	10	0.85	0.0005	39023
4	0.4	10	0.87	0.0005	39230
5	0.4	10	0.9	0.0005	39355

Table 6. Sensitivity analysis (parameter under scrutiny: final temperature)

Row	Initial temperature	Number of iterations at each temperature	Temperature reduction coefficient	Final temperature	Objective function
1	0.4	10	0.85	0.0003	38871
2	0.4	10	0.85	0.0004	40184
3 (base situation)	0.4	10	0.85	0.0005	39023
4	0.4	10	0.85	0.0006	39381
5	0.4	10	0.85	0.0007	40472

**Fig. 3.** Sensitivity analysis (parameter under scrutiny: initial temperature)**Fig. 4.** Sensitivity analysis (parameter under scrutiny: the number of iterations at each temperature)

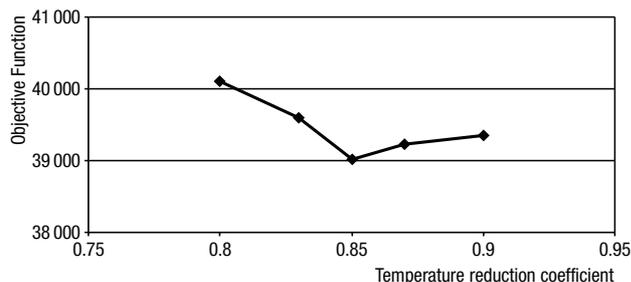


Fig. 5. Sensitivity analysis (parameter under scrutiny: temperature reduction coefficient)

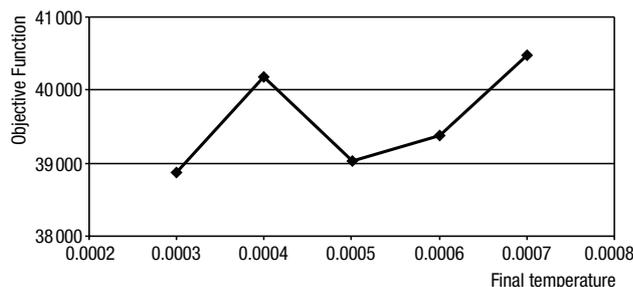


Fig. 6. Sensitivity analysis (parameter under scrutiny: final temperature)

6. Conclusions

The obtained results revealed that in each considered state, the objective function was considerably improved.

The best result occurred in state 2 with the cycle length of 120 seconds which was reduced by 14.5% in the objective function of that state.

As mentioned before, when travel demand is heavy, higher cycle length is more suitable and vice versa.

Now, considering the fact that in regard with population there are very wide roads in Hashtgerd city, the network will not be too congested and thus the optimized plan with not very long cycle length (120) is approved.

Objective function values for all states are illustrated in Table 7 and Fig. 7.

Table 7. Objective function values and related improvements for all states

Row	Cycle length (sec)	Objective function (veh-hr)	Improvement (%)
1	120 (initial state)	45483	-
2	120	38877	14.5
3	160	39780	12.5
4	200	39870	12.3
5	240	40594	10.7
6	280	41122	9.6

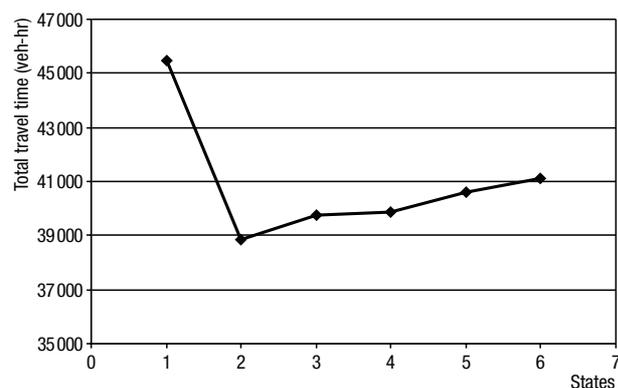


Fig. 7. Objective function values for all states

g/C values for the optimal signal timing plan are shown in Table 8.

Note that in order to obtain better outcomes, a combined strategy of signal timing optimization with contra flow operation for urban evacuation is currently being tested by the authors and will be presented in the near future.

Table 8. Objective function values and related improvements for all states

From node	To node	g/c	From node	To node	g/c
27	28	0.06	56	57	0.19
29		0.06	58		0.81
35		0.94	75		0.81
30	31	0.87	46	60	0.92
32		0.87	56		0.08
51		0.13	59		0.08
42	46	0.89	61		0.08
47		0.11	69		0.92
60		0.89	53	63	0.03
31	51	0.4	62		0.97
50		0.6	64		0.97
52		0.6	74		0.03
53		0.4	55	65	0.42
32	52	0.7	64		0.58
51		0.3	76		0.58
55		0.7			

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